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U.S. Military Use of Thermal Manikins in Protective Clothing Research

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Summary

The U.S. military has utilized thermal manikins in protective clothing research for nearly 60 years. Prior to their development, the evaluation of textile thermal insulation was limited to one-dimensional, guard-ring flat plates. During WW II, thermal manikins were instrumental in obtaining knowledge of combat clothing ensemble insulation during simulated adverse environmental conditions. Additionally, reports from the various combat theaters regarding the inadequacies of certain clothing components prompted numerous thermal manikin studies resulting in rapid improvement of many combat clothing components before the war's end. During the immediate post-war years, thermal manikin data was used to develop detailed tables of military cold weather clothing insulation and the corresponding climatic zones of issue. During the 1960's, thermal manikin research began to focus on the thermal burden imposed by protective clothing in hot environments. Research using a "sweating" thermal manikin allowed for the measurement of the maximum evaporative heat transfer obtainable by the wearer of a given clothing ensemble. In the 1970's, thermal manikin studies in combination with human wear trials provided the necessary parameters to develop the first reliable equations for predicting core temperature, skin temperature, and heart rate while wearing various military clothing ensembles. From the early 1980's to the present day, extensive research within the U.S. military using thermal manikins has resulted in a vast improvement of all major protective clothing systems for land, sea, and air based personnel. Thermal manikin data also constitutes vital input to several predictive models assessing the amount of thermal stress soldiers will experience during a wide range of environmental conditions and occupational settings. Today, sophisticated thermal manikins are used worldwide in a large number of NATO military and commercial clothing research programs. In the U.S., both the Army and Navy are currently using thermal manikins in a wide range of protective clothing research programs. The U.S. military will continue to rely on these unique research tools to identify advances that will provide future warfighters with more comfortable, functional, and effective protective clothing.

Paper presented at the RTO HFM Symposium on "Blowing Hot and Cold: Protecting Against Climatic Extremes", held in Dresden, Germany, 8-10 October 2001, and published in RTO-MP-076.

Introduction

The U.S. military services have utilized thermal manikins in protective clothing research for over 60 years. Prior to their development, the evaluation of textile thermal insulation was usually conducted in commercial settings and limited to the use of simple one-dimensional, guard-ring flat plates and three-dimensional cylinders. The development of the clo unit in 1941 by Gagge, working at the U.S. Air Force Aeromedical Laboratory, Dayton and Burton and Bazett at the Royal Canadian Air Force Institute of Aviation Medicine, Toronto, provided for a direct, universal measurement of the resistance of textile layers to dry heat transfer (1). One clo unit is defined as the amount of clothing insulation required to keep a normal sedentary man comfortable at 21° C, determined from the partitional calorimetry studies carried out by Winslow et al., in 1936 at the John B. Pierce Laboratory in New Haven (2). One clo is equal to 0.155 $m^2 \cdot K \cdot W^{-1}$.

In 1940, the various military services faced a critical logistical problem in relation to the available stockpile of protective clothing. Most major clothing ensembles had been developed for use during World War I, were composed from natural fiber materials, and were poorly coordinated in terms of providing protection for specific environmental conditions. For cold weather protection alone, there were eleven different uniforms listed with confusing recommendations for use of the 1464 total available components.

World War II-Thermal Manikins Develop as a Result of Global Conflict in Climatic Extremes

As entry into World War II appeared certain, U.S. military planners began to reevaluate much of the outdated and inadequate combat clothing still in the Army Quartermaster supply system. A decision was made to reduce the number of clothing items in the supply system and reconfigure major uniform systems to provide better protection within defined climatic ranges. To accomplish this, there was a need to quantify the thermal insulation of the standard-issue as well as prototype uniforms made from new materials, designs, and fabrication techniques when draped over a human shaped model.

The earliest U.S. military use of a heated manikin was in 1942 by Belding, who had been working under government contract at the Harvard Fatigue Laboratory, Cambridge, determining the comfort-temperature range of sleeping bags and Arctic uniforms for the Army Quartermaster and electrically-heated aviators clothing for the Army Air Force using human subjects. Belding had been using a department store fashion manikin to arrange various clothing ensembles before testing on his subjects. Belding was inspired to build his own manikin to measure the clo values of the protective ensembles he was testing. This crude manikin, lacking both arms and a head, had the general configuration of an obese man and was constructed from sheet copper, sheet metal and stovepipe by a Boston tinsmith. It was heated by means of an electrical heater in the torso and had an internal fan to produce air circulation within the manikin shell. Early studies done with this manikin produced the first clothing ensemble clo values and indicated potential advantages in terms of increased insulation and weight reduction by the use of newly developed synthetic pile fabrics, nylon, and polyester.

With the official entry of the U.S. into the war in late 1942, basic research in the field of environmental physiology and the role played by protective clothing increased tremendously at several newly formed Parallel Service Laboratories (Fort Knox Armored Medical Research Laboratory, Wright Field Aeromedical Research Laboratory, Lawrence Climatic Research Laboratory, Bethesda Naval Medical Research Institute) and at numerous universities (Harvard, Stanford, Yale) around the country. Many prominent environmental scientists (Belding, Darling, Dill, Gagge, Hall, Horvath, Talbott, Wilson) joined the various military services as civilian consultants or commissioned officers.

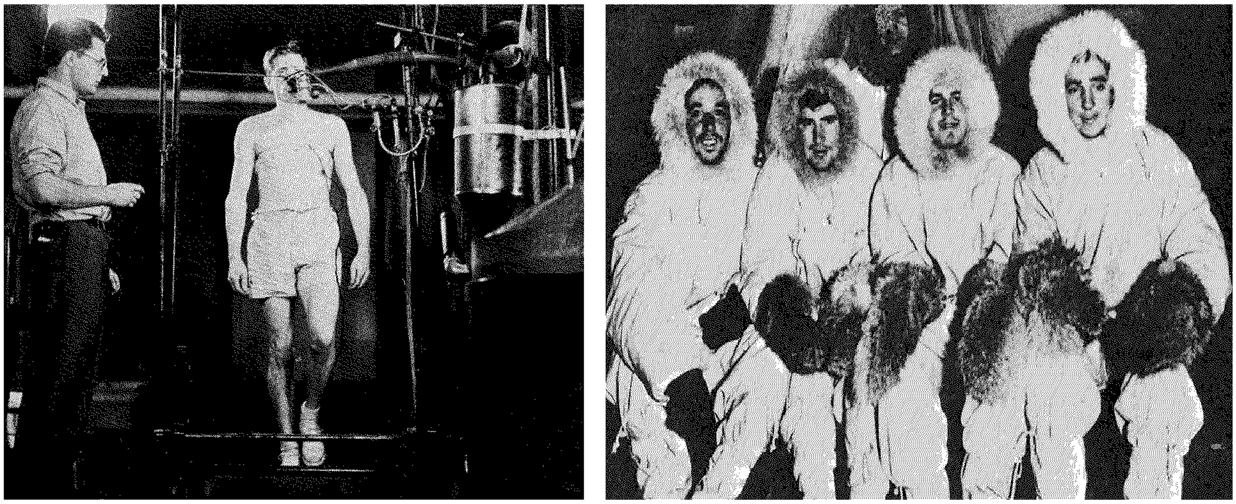


Figure 1. Basic and applied military research was conducted by civilian researchers at the Harvard Fatigue Laboratory in the early 1940's.

In 1943, the U.S. War Department was alarmed at the high incidence of non-combat injuries sustained by U.S. Army personnel sent to retake two Aleutian Islands, Attu and Kiska, that had been occupied earlier by Japanese Forces. Of the 15,000 troops deployed, 2,100 suffered from trench foot and general cold exposure (3). The troops had been sent to this unforgiving cold/wet climate outfitted in World War I vintage protective clothing composed of wool and cotton while wearing uninsulated leather boots. In mid 1943, the Harvard Fatigue Laboratory funded Belding to acquire a more life-like manikin to conduct further studies to improve military protective clothing. Belding contacted researchers at the General Electric Company in Bridgeport, Connecticut. General Electric agreed to construct an electrically heated manikin similar to one they had been using since the late 1930's in their research and development program to develop an affordable electric blanket for the consumer market. This new manikin, cast from the exquisite clay figure done by Connecticut sculptor Leopold Schmidt, was known as the "Harvard Copper Man". The manikin, delivered to the Harvard Fatigue Laboratory in late 1943, was composed of an electroplated copper shell from 3 to 6 mm in thickness and had a single electrical circuit which uniformly heated the actual shell with a provision to vary the temperature of the hands and feet without affecting the surface temperature of the rest of the manikin's body. Belding and his associates at Harvard used their thermal manikin throughout 1944 to evaluate numerous military protective clothing items, investigate reports of inadequacies in protective clothing capabilities coming in from various battlefronts, and suggest possible improvements to the Army Quartermaster clothing specialists. In the process, Belding along with fellow scientists using thermal manikins for Canadian and British military research efforts developed the fundamental basis for today's scientific study of protective clothing.

As World War II drew to a close, many members of the Harvard Fatigue Laboratory including Belding and his thermal manikin joined the Army Quartermaster General's new Climatic Research Laboratory in Lawrence, Massachusetts to continue pioneering work on improving environmental protection for military personnel. In September 1945, General Electric was asked to build the next generation thermal manikin for the Climatic Research Laboratory. General Electric combined its previous manikin expertise along with detailed data from an anthropometric study of nearly 3000 Army Air Force cadets (4) to construct another electroplated copper shell manikin with a total of six separate electrical circuits and based on the average physical dimensions of a young U.S. military recruit. General Electric also delivered a similar manikin to the U.S. Army Aeromedical Laboratory at Wright Field in Dayton where Gagge and his associates used it to completely redesign most Army Air Force aviators clothing away from the use of natural to newly developed artificial materials.

During 1946, researchers at the Climatic Research Laboratory conducted more extensive testing with their new "Copper Man" including very precise determinations of the surface area and surface emissivity as well as nude and clothed clo value studies with the manikin in various orientations, under varying wind velocities, and throughout a wide range of ambient temperatures and humidities. Additional investigations were done in the late 1940's to determine total clo values of most major military cold weather clothing ensembles, standardize the caloric output of the new manikin by evaluating human subjects under similar environmental conditions, and investigate methods to minimize the effects of wind penetration through closures and interstices of outerwear fabrics.

The unique instrumentation, measuring techniques, and theoretical concepts developed during the 1940's allowed for the first effective advances to be made in the research and development of improved protective clothing for the military.

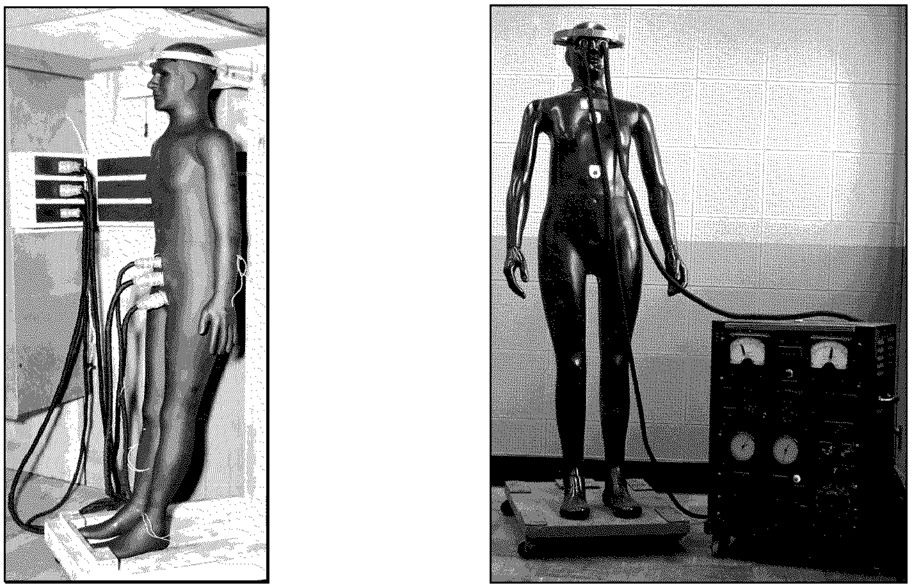


Figure 2. Thermal manikins in use at the U.S.Army Quartermaster's Climatic Research Laboratory in the late 1940's. Left: single circuit "Harvard Copper Man" built by General Electric Co., 1943. Right: six circuit "Copper Man" also built by General Electric Co., 1946.

The 1950's-Worldwide Clothing Requirements Established From Thermal Manikin Data

By the early 1950's, clothing researchers had successfully used thermal manikins to measure the resistance to sensible, dry heat transfer of a wide range of protective clothing from all the military services. In the process, military footwear, handwear, sleeping bags, and combat clothing ensembles were further improved for comfort, durability, and environmental protection.

The Korean War (1950-53), however, again demonstrated the inability of military clothing, handwear and footwear to provide environmental protection for a large-scale deployment of personnel to a harsh climatic region. Severe cold-dry winter conditions on the Korean Peninsula resulted in thousands of cases of cold exposure, trench foot, and frostbite of extremities to U.S. military personnel.

Recognizing that U.S. military protective clothing, including boots and gloves, for use in extreme cold conditions still needed improvement, the U.S. Army Quartermaster in 1951 contracted with General Electric to build two new thermal manikins as well as thermal foot and thermal hand models, again all from electroplated copper. The new thermal foot model, in conjunction with extensive human testing, was used in a successful effort to develop the U.S. Army Extreme Cold Weather Boot in 1953 (6). This boot, which was designed to provide protection at -50° C, had insulation layers hermetically sealed within impermeable layers of rubber and dramatically reduced the incidence of cold injury to the feet of personnel exposed to extreme cold weather.

In 1954, the Climatic Research Laboratory was relocated to Natick, just west of Boston, and renamed the Quartermaster Research and Development Command. This new facility housed military scientist tasked with the research and development of U.S. Army clothing, personal life support equipment, food technology, and airdrop technology. The addition of large climatic chambers in 1955, designed to simulate any climate that military personnel could encounter, further enhanced this facility as the premier military laboratory for protective clothing research.

By 1955, planners from all the U.S. military services had access to extensive tables of specific temperate and cold weather uniform insulation values. These thermal manikin values were then integrated with actual human physiological response data when wearing identical clothing ensembles. At the same time, military earth scientists developed detailed global maps outlining the major climatic zones and their monthly meteorological changes. The result was a series of 25 Protective Clothing Almanacs for each month and every continent that delineated specific areas of use for certain protective ensembles and associated components. This work also produced associated clothing requirement charts, tables, and periodic reports forwarded to major commands to better facilitate the proper procurement and issuance of military protective clothing.

Today, these early clothing distribution guideline efforts have been refined to form part of the Common Table of Allowances, the single Department of the Army document for climatic-based issue of military protective clothing (7).

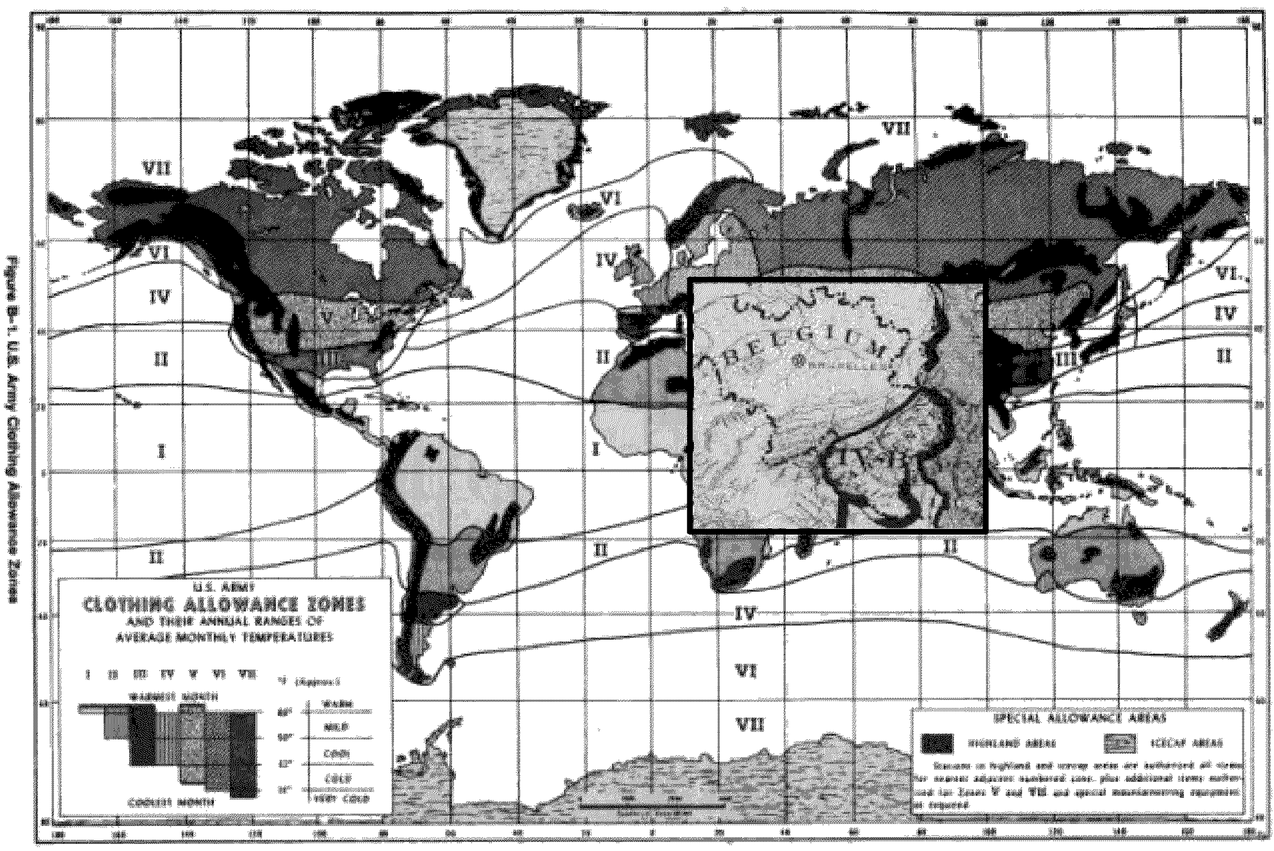


Figure 3. Global and regional maps from a series of U.S. Army Quartermaster General Clothing Almanacs delineating various clothing allowance zones based on local environmental conditions. From reference 5.

Thermal manikin research during this decade also revealed that the highly curved surfaces of the human body created a complex and dynamic microclimate between the clothing and skin surface. Unlike the heat transfer characteristics of textiles established from earlier guarded ring flat plate work, thermal manikins

showed that actual clothing, when draped over the human figure, can have localized variations in thermal conductivity as well as in the ensemble's convective and radiative properties.

The 1960's-Use of Sweating Thermal Manikins to Measure Water Vapor Resistance of Protective Clothing

In 1961, most military thermal manikin work was centered at the new U.S. Army Research Institute of Environmental Medicine (USARIEM) located at Natick, MA. One area of new research was focused on the resistance by protective clothing to the transport of water vapor and its impact on soldier performance. This work was possible due to the introduction of the moisture permeability index, i_m, by Woodcock who was working at USARIEM in 1962 (8). This index is the ratio of the maximum evaporative cooling, at a given ambient vapor pressure, from a 100% wetted surface through a fabric, to the maximum evaporative cooling of a psychrometric wet bulb thermometer at the same vapor pressure. This parameter characterized the permeability of clothing materials to the transfer of water vapor.

Woodcock used a sweating, heated cylinder to conduct his i_m evaluations of both the bare cylinder surface and various protective clothing textiles. Goldman and Breckenridge, interested in utilizing this index for practical clothing applications, outfitted thermal manikins with tight fitting cotton skins that could be saturated with water to simulate a sweat wetted skin surface. These "sweating" manikins could now measure the maximum evaporative heat transfer allowed to an individual wearing a given protective ensemble. This work made it possible to begin a concerted effort to increase the "breathability" of chemical and biological protective clothing as well as assess the thermal burden imposed by the addition of load carriage and ballistic protective equipment to standard clothing systems.

Goldman and his associates at USARIEM proceeded to conduct extensive thermal manikin evaluations on most major military protective clothing systems including a wide range of low permeability garments with and without various combinations of backpacks and personal body armor. At the same time, controlled human volunteer trials were conducted while wearing the same protective clothing configurations in a variety of temperate, warm and hot environmental conditions (9).

Using the knowledge generated by these new sweating thermal manikins of uniform thermal and water vapor resistances combined with the growing data base of human thermophysiological responses while resting and working in stressful environments, it was then possible to rank order military protective ensembles in terms of heat tolerance of the wearer (10).

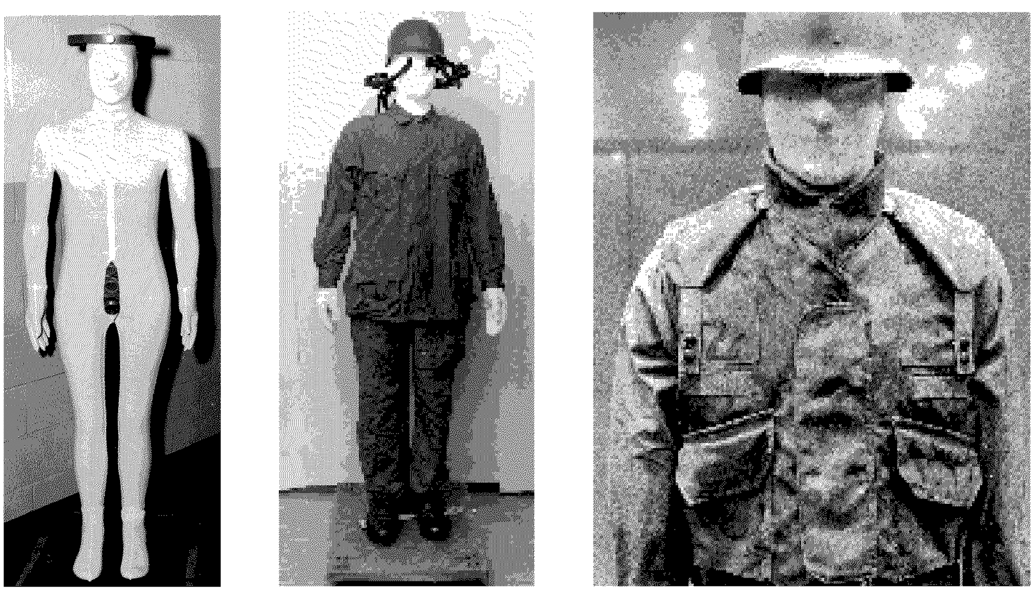


Figure 4. Technique of using wetted cotton skin on thermal manikins to simulate sweating and measure water vapor resistance imposed by hot weather combat clothing and ballistic protective equipment.

The 1970's-Thermal Manikin Data Used to Assist in Human Performance Prediction.

Comparisons made between thermal manikin data and controlled human volunteer studies indicated that the movement of air within and immediately adjacent to a multilayered clothing system could have a dramatic impact on the evaporative cooling potential of the protective ensemble. Consequently, Givoni and Goldman developed a pumping coefficient (p) that described the effects of wearer-generated air motion on the thermal and water vapor resistances of clothing (10).

Givoni and Goldman then used clothing thermal and water vapor resistances from thermal manikins along with the derived pumping coefficient to develop a series of equations that predicted rectal temperature when wearing military clothing in a range of cool to very hot environments (11). These early equations were further modified by Givoni and Goldman to predict heart rate while wearing protective clothing and working in stressful environments (12).

In the mid-1970's, thermal manikin data continued to be critical coefficient input as these equations were developed into more sophisticated predictive models. Important modifications were made by Pandolf et al. (13) to assess the impact of level of dehydration and by Givoni and Goldman (14) on the effects of acclimatization on wearers of protective clothing.

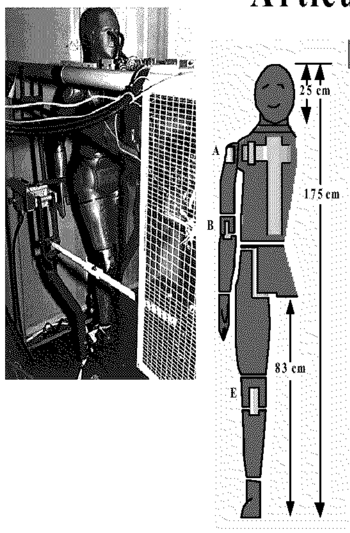
1980 to the Present-Thermal Manikin Data Assists in the Development of Advanced Protective Clothing, Predictive Performance Models, and Portable Environmental Stress Monitors

In the early 1980's, the U.S. Army began a complete redesign of major clothing systems for air, ground, and vehicle based personnel utilizing a variety of novel technologies and materials. On an increasing basis, the military has evaluated and adopted numerous commercial textile developments for use in these new combat clothing, footwear, handwear, and sleeping systems. Several U.S. textile manufacturers have specialized, in-house groups interfacing directly with military clothing developers to provide access to novel developments and test results. Military clothing developers were again faced with the ever-present challenge of reducing weight and bulk while increasing the personal protective capabilities of all clothing ensembles and associated components. Numerous biophysical studies were done to evaluate new commercial developments in lightweight, fine-fiber polyester insulations, waterproof/breathable membranes, and durable textiles for use in footwear, handwear and special operations clothing and equipment.

Beginning in 1983, extensive USARIEM thermal manikin evaluations were instrumental in the eventual fielding of the new Extended Cold Weather Clothing System, Intermediate Cold Weather Boot and Glove, all Battledress Uniforms, Joint Services Chemical Protective Suit, and both Intermediate and Extreme Cold Weather Sleeping Systems. All of these new systems incorporate advanced textile materials and design concepts developed in partnership with numerous commercial enterprises located in the U.S. In the past 20 years, USARIEM has provided biophysical thermal manikin data to clothing developers from all the U.S. military services on hundreds of clothing, footwear, handwear, and sleeping systems.

In 1984, USARIEM began using a new articulated, thermal manikin (Figure 5), fabricated by the Arthur D. Little Company, Cambridge under specifications designed by USARIEM scientists. This manikin, employing 19 separate heating zones, has the ability to simulate the bodily movements involved in walking and running. The manikin is housed in a climatic chamber with precise control over the air velocity directed at the manikin. A minimum of three different air velocities are usually necessary to accurately determine the effect of air movement on the thermal and moisture transfer properties of protective clothing ensembles. Table 1. shows typical thermal manikin evaluation data at differing air velocities.

Area and Power Constants for USARIEM Articulated Manikin



	Articulation Section	Surface Area (m²)	%Total	Design Heat (W)
	Head	0.139	8.3	69.4
	Torso	0.336	19.9	168.0
A	Upper Arms	0.144	8.6	72.0
	Lower Arms	0.062	3.7	31.1
	Hands	0.102	6.1	51.0
B	Elbows*	0.034	2.0	17.0
	Waist	0.020	1.2	10.0
C	Abdomen	0.107	6.4	53.4
D	Right Hip	0.084	5.0	41.8
	Left Hip	0.084	5.0	41.8
	Thighs	0.219	13.0	109.5
E	Knees**	0.052	3.1	26.1
	Calves	0.167	9.9	83.6
	Feet	0.131	7.8	65.5
	Whole Body	1.68	100	approx 500 W/m²
	Upper Body	0.94	56	approx 500 W/m²
	Lower Body	0.74	44	approx 500 W/m²

Figure 5. Photograph and technical specifications of the USARIEM articulated thermal manikin.

SYSTEM	1989			REDONE 1994					
	Windspeed,m/s								
	0.6,"still"			1.12			2.24		
	It, (clo)	im	im/It	It, (clo)	im	im/It	It, (clo)	im	im/It
1. IMPERMEABLE BUTYL									
A) WORN ALONE,OPEN	1.58	0.13	0.08	1.36	0.13	0.10	1.22	0.15	0.12
B) WORN CLOSED	2.05	0.08	0.04	1.76	0.09	0.05	1.59	0.10	0.06
C) WORN ALONE, TERRYCLOTH COVERALL	2.05	0.27	0.13	1.76	0.28	0.16	1.59	0.32	0.20
2. FRENCH									
A) WITH INTEGRAL HOOD,OPEN	2.42	0.36	0.15	2.08	0.38	0.18	1.87	0.44	0.23
B) WITH OUT INTEGRAL HOOD, OPEN	2.31	0.39	0.17	1.99	0.41	0.21	1.79	0.47	0.26
C) WITHOUT INTEGRAL HOOD, CLOSED	2.57	0.33	0.13	2.21	0.35	0.16	1.99	0.40	0.20
3. UNITED KINGDOM*									
MKIV					0.00				
A)WITH INTEGRAL HOOD, OPEN	2.18	0.39	0.18	1.87	0.41	0.22	1.69	0.47	0.28
B) WITHOUT INTEGRAL HOOD, OPEN	2.08	0.40	0.19	1.79	0.41	0.23	1.61	0.47	0.29
C) WITHOUT INTEGRAL HOOD, CLOSED	2.27	0.32	0.14	1.95	0.33	0.17	1.76	0.38	0.22
4. THE NETHERLANDS									
A) WITH INTEGRAL HOOD, OPEN	2.35	0.35	0.15	2.02	0.37	0.18	1.82	0.42	0.23
B) WITHOUT HOOD, OPEN	2.23	0.38	0.17	1.92	0.40	0.21	1.73	0.45	0.26
C) WITHOUT HOOD, CLOSED	2.49	0.27	0.11	2.14	0.29	0.13	1.93	0.33	0.17
5. U.S. ARMY BATTLE DRESS OVERGARMENT ,BDO*									
6. CANADA*									

*SEE TTCP REPORT T94-4 also for latest values
UK includes Australia, New Zealand

Table 1. USARIEM thermal manikin data from NATO NBC protective clothing evaluations. From reference 15.

A key development of this research has been the incorporation of thermal manikin data and subsequent clothing coefficient integration into a heat stress monitor (HSM) from 1983 to the present. The miniature heat stress monitor (HSM) is a pocket sized, stand alone electronic device for local heat stress assessment/management. The HSM integrates the USARIEM heat strain prediction model software with a comprehensive suite of environmental sensors and microprocessor technology to provide tailored guidance to reduce heat injury risk across the spectrum of heat stress environments including chemical protective encapsulation.

The HSM has an injection molded plastic case with an integrated hinge and latch closure mechanism. In its closed configuration, HSM dimensions are 12 x 9 x 4 cm. Opening the rear cover allows the sensor module to be rotated into position for environmental measurements, and also provides access to the battery compartment. The system is powered by four standard AA alkaline batteries and has a total weight of 0.37 kg. The field replaceable sensor module assembly consists of air temperature, humidity, wind speed, miniature black globe temperature, and barometric pressure sensors, and their analog/digital processing circuitry. The display is a text and graphics capable liquid crystal display (LCD) and has a back-light feature for use at night. User inputs and HSM function selection are accomplished through a miniature 5 button GPS- type keypad to the right of the LCD. An RS-232 port on the lower side of the case provides PC communications and a miniature threaded tripod mount on the bottom of the case allows secure attachment for unattended data logging applications.

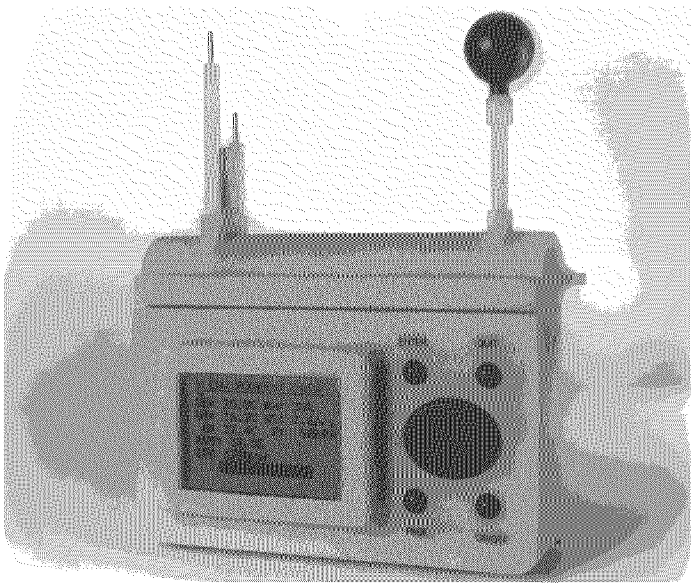


Figure 6. USARIEM Heat Stress Monitor used for prediction of work/rest cycles, water requirements and maximum work possible in any ambient temperature.

The HSM microprocessor system automatically displays current date/time and battery status on power-up. Entering the heat strain model option of the HSM, the user selects menu items for clothing type, work/task category (resting, very light, light, moderate, or heavy work), and acclimatization status (yes or no). After a 2 minute measurement period, the HSM displays hourly drinking water requirements, optimal work/rest cycle limits, and maximum safe work time for continuous work, as well as the 2-minute averaged environmental data used for these computations. A real-time sensor mode may also be selected to view real-time display of air temperature, wind speed, relative humidity, wet bulb temperature, black globe temperature, mean radiant temperature, WBGT index, and barometric pressure. Additional operating modes include: 1) System setup allows the user to set current date/time, and metric or English units for displayed parameters. 2) Datalog setup allows the user select a start time, log time interval, and duration. 3) Datalog review allows the user to view all logged data including predictive model outputs. 4) Data log download allows download of logged data through the RS-232 port to a PC for display with HSM software or import to

a spreadsheet for analysis. 5) Service mode allows PC access through the RS-232 port for program updates, calibration, and system diagnostics.

The HSM is an ideal device that can be employed to help reduce the risk of heat injury in military or industrial settings as well as in sports/physical training applications. The HSM can be used outdoors, in crew compartments and other enclosed work space environments in real-time. With its automated datalog capability, it can also be used to provide operational test documentation or survey data for heat stress conditions over a 24 hour period. HSM measurements of the ambient environment could be used in a variety of human factors engineering/development projects and the programmable microprocessor provides an integrated platform that is easily adaptable for use with a wide range of user-specific models and algorithms.

United Kingdom Mark IV Overgarment
Mask, Gloves, Attached Hood
Ta= 35.0° C RH= 50% Wind Speed= 1.0 and 4.0 m/s Solar Load

Work Rate	Casualties	Work/HR		Water/Hr Canteens		Max.Work (min)		Water/Hr Canteens	
	Wind m/s	1	4	1	4	1	4	1	4
Light	< 5%	NFW	NL	NA	1.1	108	NL	1.5	1.2
Moderate	< 5%	NFW	22	NA	1.0	49	66	2.1	1.8
Heavy	< 5%	NFW	14	NA	1.0	34	41	2.1	2.1
Light	20%	NL	NL	1.4	1.0	NL	NL	1.5	1.1
Moderate	20%	NFW	37	NA	1.3	69	115	2.1	1.7
Heavy	20%	NFW	22	NA	1.1	45	56	2.1	2.1
Light	50%	NL	NL	1.3	1.0	NL	NL	1.4	1.1
Moderate	50%	13	NL	1.1	1.5	102	NL	2.0	1.7
Heavy	50%	5	32	1.0	1.4	57	77	2.1	2.1

Work Rates: **Light= 250watts Moderate= 425watts Heavy=600watts**
Work/hr: number of minutes of work with remainder assumed as resting period; NFW= no further work possible; NL= no limit to work times
Casualty Rates: **Light= < 5% reaching 39° C core temperature**
Moderate= 20% reaching 39.5° C core temperature
Heavy= 50% reaching 40° C core temperature

Table 2. USARIEM Heat strain modeling results incorporating thermal manikin clothing coefficients from United Kingdom chemical protective clothing. From reference 17.

Advanced Predictive Modeling

In recent times, a computer model called SCENARIO, developed by Kraning and Gonzalez (16), has been developed that is specifically designed to simulate the time course of heat strain observed during athletic, industrial, and military settings. The simulations generated by the model dependably reproduce the time course of body temperature shifts, thermoeffector responses, central and peripheral circulatory changes in persons exercising in warm and hot environments. The model also takes into consideration numerous U.S. military protective clothing ensembles that have been evaluated by the various thermal manikins at USARIEM described in this report and is currently being employed to predict physiologic responses for various levels of aerobic fitness in a given population. The model is also currently being enhanced to account for the effects of progressive dehydration. Due to recent standardization of the procedures of thermal manikin operation, different groups can conduct protective clothing research with an increasing degree of confidence in both the compatibility and reliability of interlaboratory data. In terms of continued technological advancement of military protective clothing, numerous NATO countries possess or have direct access to thermal manikins. The U.S. military is routinely involved in various data exchange programs with NATO and The Technical Cooperation Program (TTCP) countries where protective clothing is evaluated and results modeled in a round-robin fashion (17).

Conclusions

Today, sophisticated thermal manikins are used in a large number of military and commercial clothing research programs worldwide. They are routinely used to assess the biophysical properties of consumer, as well as commercial and military protective clothing. Specialized thermal heads, hands and feet are used on a more limited basis for the evaluation of clothing designed to minimize important extremity heat loss.

Since 1942, thermal manikins have evolved within the U.S. military as a direct result of the need to provide better personal protective clothing and equipment in an increasing variety of environmental zones of operation. Thermal manikin data have been instrumental in improving both the comfort and functional performance of a multitude of military clothing and equipment as well as providing input to develop tactical clothing issue doctrine and practical human performance predictive models.

The U.S. military will continue to rely on these unique research tools to test and identify technological advances that will provide future warfighters with more comfortable, functional, and effective protective clothing systems.

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